JOBY AVIATION

Joby Aviation is a privately-held company headquartered in Santa Cruz, California. In 2009, leveraging the control systems and electric propulsion systems developed at Joby Energy, Joby Aviation was founded to revolutionize how we commute. Joby Aviation's strengths in composite airframe design and fabrication, high-fidelity aerodynamic analysis, and through the sister company Joby Motors (www.jobymotors.com), high-performance electric motor design and fabrication, place it in a unique position to create a new generation of electric personal aircraft.

ALEX STOLL

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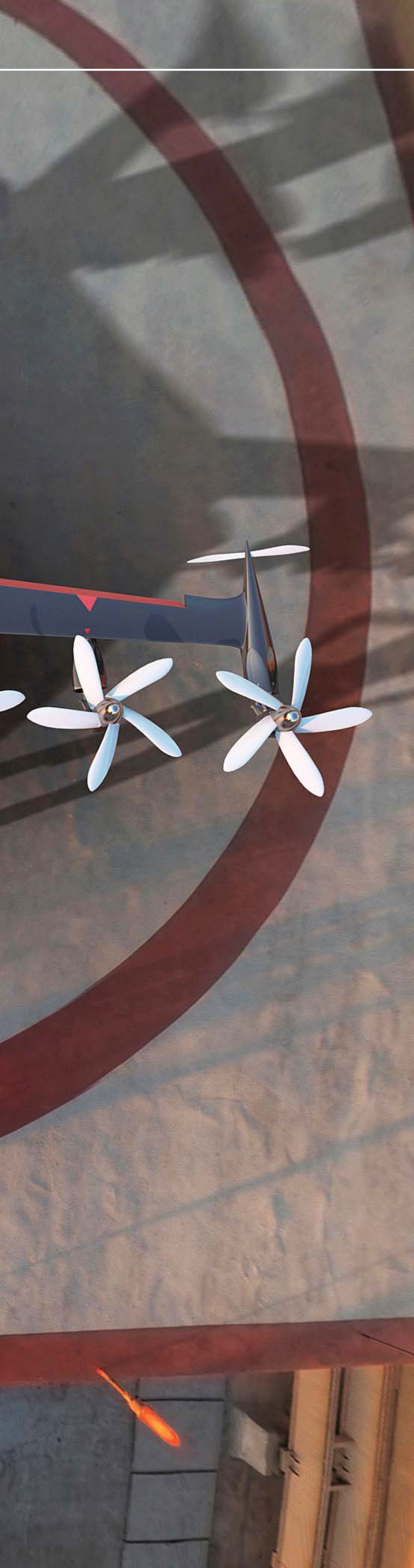

QUIET, RELIABLE AND EFFICIENT! JOBY AVIATION PAVES THE WAY FOR AN ELECTRIC FUTURE

ALEX STOLL
Joby Aviation

INTRODUCTION

Electric propulsion is on the verge of causing the biggest changes in aviation since the advent of the jet engine. At first glance, it may seem that the excessive weight (i.e. low specific energy) of today's batteries limits electric aircraft to, at best, a few trivial niches. However, the different properties of electric propulsion compared to traditional combustion power, coupled with recent technology advances, promise to significantly relax typical design constraints for many aircraft configurations, which will allow for new types of aircraft that were previously impractical or impossible. This is particularly true for shorter-range designs, which have traditionally been relatively small and piston-powered.

WHY ELECTRIC PROPULSION?

Because of the size, weight, and maintenance requirements of piston engines, most piston aircraft designs are limited to a small number of engines (often just one) located in a small number of practical locations. This is why most modern general aviation airplanes and helicopters look very similar to designs from the 1950s. In contrast, electric powertrains are much smaller and lighter, and they are incredibly simple – some having only a single moving part – compared to the relatively extreme complexity of piston engines, which include a coolant system, an electrical system, an oil system, a fuel system, and so forth. This reduced complexity translates to much lower maintenance requirements.

While smaller combustion engines suffer from lower power-to-weight and efficiency, electric motors are relatively scale-free. This means that the power-to-weight and efficiency will be similar between, for example, a 1 kW motor and a 1,000 kW motor. An electric powertrain is also about three times as efficient (around 90%-95% compared to around 30%-40%). Electric motors can operate well on a much wider range of RPMs, and they can change RPM relatively quickly.

Electric powertrains are significantly quieter than combustion powertrains, as anyone who has heard an electric car can attest.

While simply replacing a combustion engine with an electric motor will see the benefits of lower noise and higher powertrain efficiency, much greater advantages can be gained by designing an aircraft with electric propulsion in mind from the start. The different properties of electric propulsion mean that aircraft can effectively employ a large number of small motors without incurring an undesirable amount of complexity (and maintenance costs) and without compromising on motor weight or performance. These motors can be located in a much larger range of positions on the aircraft, due to their relatively low weight and small size. Additionally, the drawbacks of carrying motors that are only used in some portions of the flight (e.g. takeoff and landing) are relatively minor, since the motors themselves are so light.

While traditional propulsion installations often compromise aircraft performance – for example, the scrubbing drag caused by a tractor propeller increasing the velocity over the fuselage – the flexibility of electric propulsion allows for propulsion installations that actually result in beneficial aerodynamic interactions. One such example is locating propellers on the wingtips, where they can recapture some of the energy lost to the wingtip vortices.

With its expertise in electric motor design and fabrication, high-fidelity aerodynamic analysis, and composite airframe design and fabrication, Joby Aviation is fully capitalizing on the promise of this new technology to develop several aircraft providing capabilities that were never before possible. However, due to the complex nature of these interactions and the lack of previous designs to extrapolate from, a large amount of high-order aerodynamic analysis must be performed in the design process. For this reason, Joby Aviation has leaned heavily on CFD analyses using STAR-CCM+® in the development of its unconventional designs.

FIGURE 1: A rendering of the Joby S2

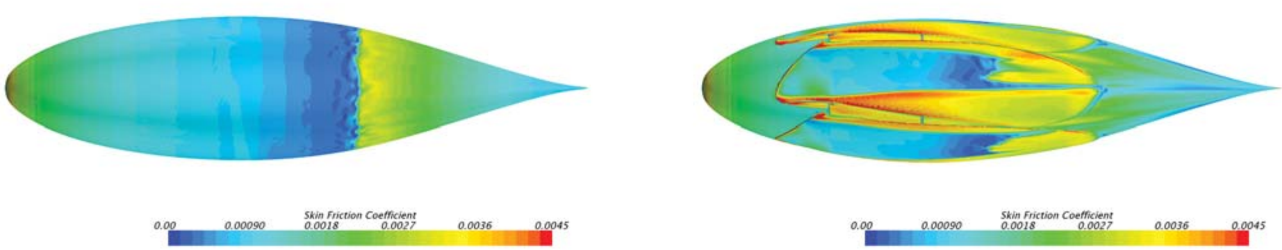

FIGURE 2: CFD analysis of the S2 nacelles, showing a clean nacelle (left) and a nacelle with folded blades and spinner gaps (right)

JOBY S2

Joby Aviation's main development effort is the S2 Vertical Takeoff and Landing (VTOL) aircraft, shown in Figure 1, which addresses the high noise, high operating costs, low speed, and relatively low safety levels that, together, have severely limited the proliferation of conventional VTOL aircraft of this size (helicopters). The S2 employs multiple propellers in takeoff and landing to increase safety through redundancy. In cruise, most of these propellers fold flat against their nacelles to reduce drag. The design of these propeller blades is a compromise between propeller performance and the drag of the nacelles with the blades folded, and higher-order tools were required to properly analyze this tradeoff. A variety of propeller designs were assessed under various operating conditions in STAR-CCM+, and the nacelle was analyzed in the cruise configuration using the γ-Re_θ transition model. One such nacelle geometry can be seen in Figure 2, where both the unmodified clean nacelle and the same nacelle with the folded blades and spinner gaps are shown. Such results indicate where reshaping the propeller blades may increase laminar flow and reduce cruise drag.

JOBY LOTUS

Another Joby Aviation project is the Lotus aircraft, shown in Figure 3, which is exploring a novel VTOL configuration on the 55-pound UAV scale. In this aircraft, two-bladed propellers on each wingtip provide thrust for vertical takeoff. After the aircraft picks up enough forward speed for sufficient wing lift, each set of two blades scissors together and the individual blades become wingtip extensions, forming a split wingtip. A tilting tail rotor provides pitch control during takeoff and landing and propels the aircraft in forward flight. The takeoff and cruise configurations of the Lotus are illustrated in Figure 4. As one may expect, the design of these wingtip blades – the span, airfoil choice, twist and chord distribution, pitch, and dihedral – was an interesting compromise between propeller and wingtip performance. Dozens of CFD simulations were run on different combinations of these design variables in the cruise configuration, to maximize the cruise performance within the constraints of the configuration. At the same time, the performance of these blades in the propeller configuration was also analyzed with CFD to validate lower-order design methods. Example results from some of these simulations are shown in Figures 5 and 6.

LEAPTECH

The third project Joby Aviation is participating in is LEAPTech (Leading Edge Asynchronous Propeller Technology), a partnership with NASA and Empirical Systems Aerospace. The goal of this design is to investigate potential improvements in conventional fixed-wing aircraft through electric propulsion. A row of small propellers is located along the leading edge of the wings and, during takeoff and landing, these propellers increase the velocity (and, therefore, the dynamic pressure) over the wings. This increases the lift produced by the wing and allows for a smaller wing to be used for the same stall speed constraint. Since many small aircraft use a wing sized to meet a stall speed constraint but too

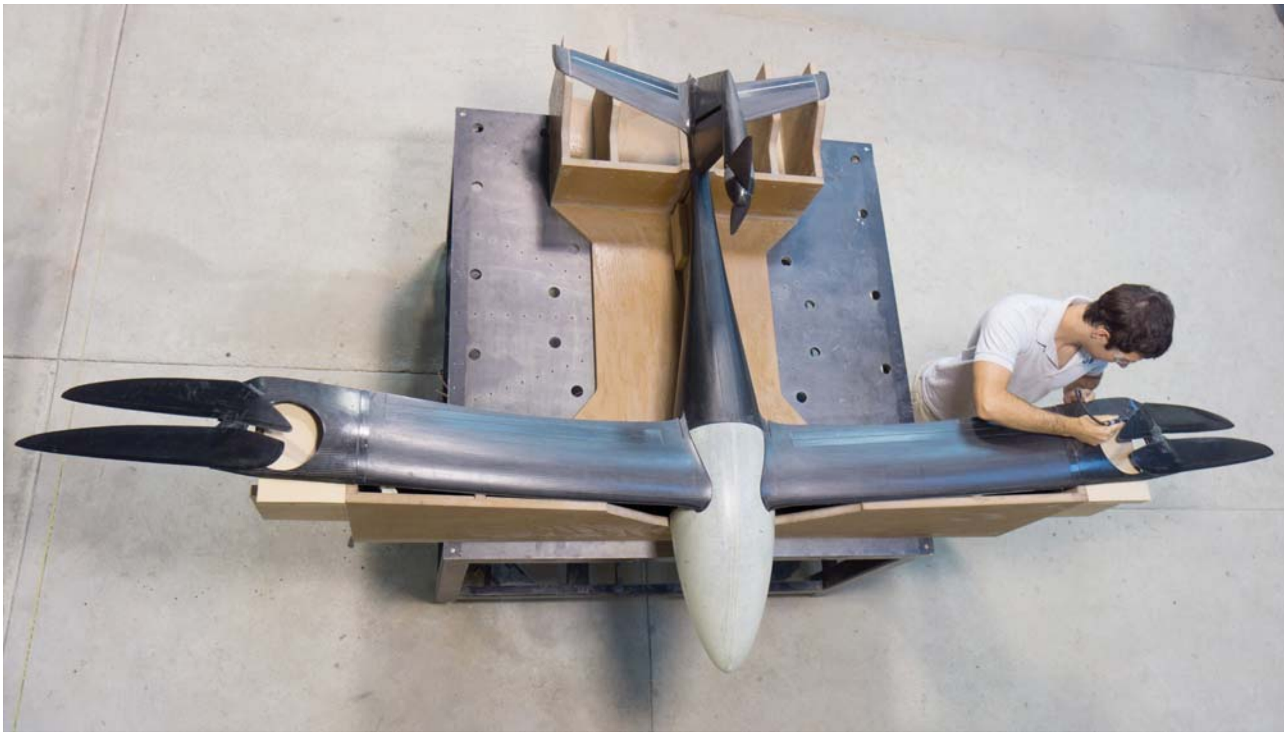

FIGURE 3: The Lotus during assembly, in cruise configuration

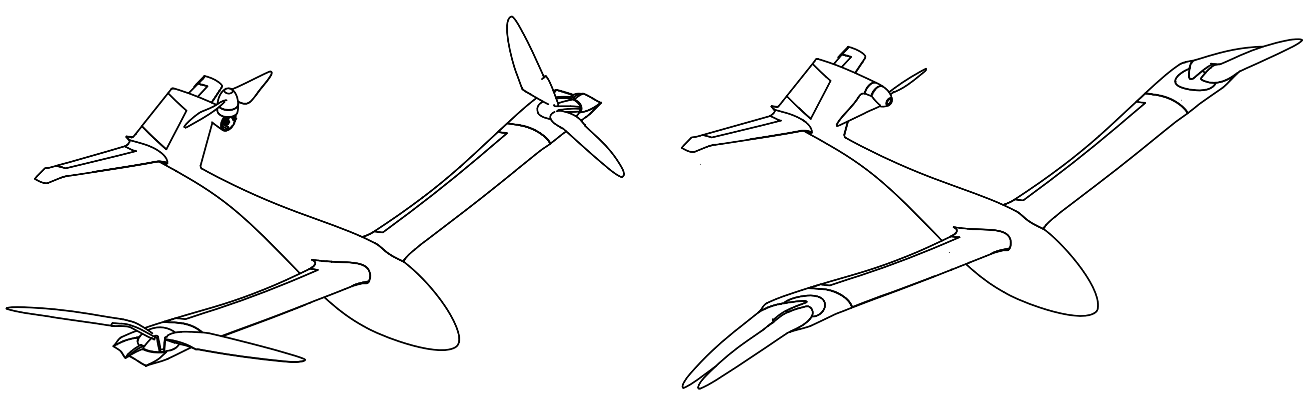

FIGURE 4: The Lotus in takeoff (left) and cruise configurations (right)

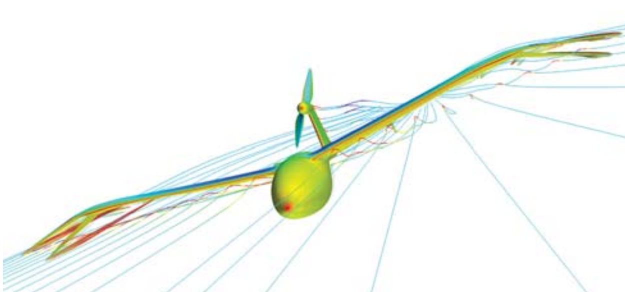

FIGURE 5: CFD analysis of the Lotus in cruise configuration

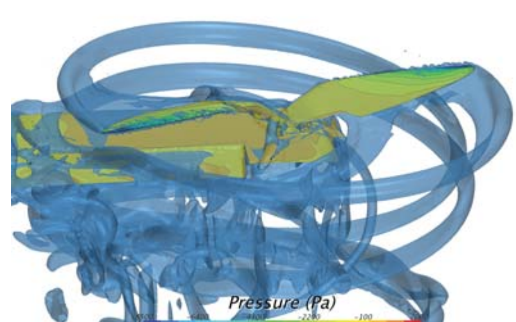

FIGURE 6: CFD analysis of the Lotus wingtip propeller at takeoff

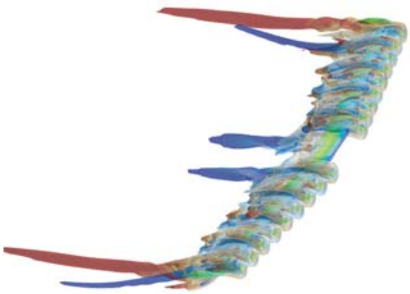

FIGURE 7: CFD simulation of the LEAPTech wing at takeoff; the propellers are modeled with actuator disks.

FIGURE 8: The LEAPTech experimental test apparatus at NASA Armstrong (NASA photo)

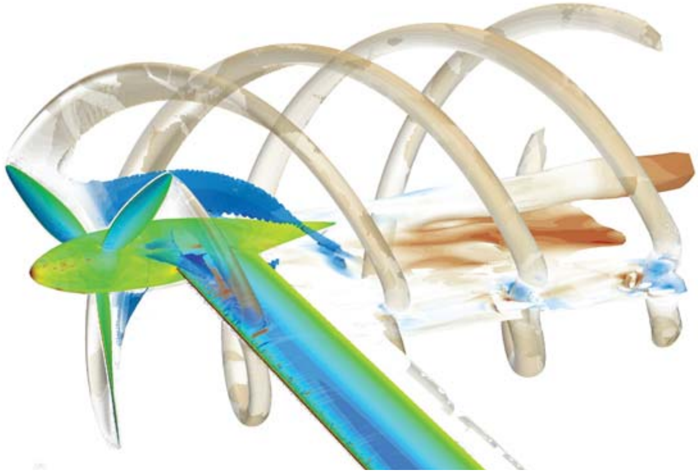

FIGURE 9: CFD simulation of a wingtip propeller

large for optimal cruise performance, this smaller wing allows for more efficient cruise. Additionally, the ride quality is significantly improved due to the higher wing loading. However, the performance of this blown wing is difficult to analyze with lower-order tools, particularly since much of the required analysis occurs around stalling conditions. Therefore, a large number of CFD simulations were performed in the design process, looking at various combinations of propeller sizes and powers, wing aspect ratios and sizes, angles of attack, etc. To reduce the computational expense, the propellers were modeled as actuator disks with the body force propeller method in STAR-CCM+, which negated the need to resolve the actual blade geometry, drastically decreasing the required mesh size.

The first phase of testing this configuration was to build the full-scale wing, propellers, and motors, and mount them above a modified semi-truck which was run at takeoff speeds on the runway at NASA Armstrong Flight Research Center. An example CFD solution of this configuration is shown in Figure 7, and the experimental test apparatus is shown in Figure 8. Outside of takeoff and landing, these leading-edge propellers are planned to fold against their nacelles – similar to the S2 propellers – and wingtip propellers, as mentioned above, will provide propulsion. Although lower-order analysis methods were evaluated for estimating the drag and efficiency impact of operating these propellers concentric with the wingtip vortex, unsteady CFD proved to be the most reliable analysis method. A range of design parameters were analyzed, and one such solution is shown in Figure 9. A flight demonstrator is planned for flights beginning in 2017; a rendering of this aircraft is shown in Figure 10.

CONCLUSION

Joby Aviation is quickly advancing the state of general aviation aircraft with its revolutionary electric propulsion concepts, and simulation is playing a big role in understanding the complex nature of their state-of-the-art ideas and in the design and development of their unconventional systems. The S2, Lotus, and LEAPTech designs show great promise towards an electric future in aviation never before possible.

"Joby Aviation's unconventional aircraft designs benefit from an unusual degree of coupling between the propulsion and airframe design; however, this coupling complicates the analysis, since low-order tools are not powerful enough and statistical methods are less useful due to the lack of significant historical data. For these reasons, STAR-CCM+ has been an extremely valuable component of our design and analysis toolkit."

FIGURE 10: Rendering of the LEAPTech demonstrator (NASA photo)